FEASIBILITY STUDY OF A CURRENT MODE GAMMA RADIATION DOSIMETER BASED ON A COMMERCIAL PIN PHOTODIODE AND A CUSTOM MADE AUTO-RANGING ELECTROMETER

by

Marko S. ANDJELKOVIĆ [*] ***and Goran S. RISTIĆ***

Applied Physics Laboratory (APL), Faculty of Electronic Engineering, University of Niš, Niš, Serbia

Scientific paper
DOI: 10.2298NTRP/1301073A

An experimental study has been conducted to evaluate the feasibility of a current mode gamma radiation dosimeter, consisting of a commercial PIN photodiode as a radiation sensor, and a custom made auto-ranging electrometer for real-time measurement of the PIN photodiode's response under radiation exposure. The radiation induced direct current response for single PIN photodiodes with different active areas, as well as for multiple PIN photodiodes connected in parallel, has been investigated. Three types of commercial silicon PIN photodiodes have been chosen for evaluation – S1223, BPW34, and PS100-6-CER2 PIN. During the experiment, five samples have been tested – three samples made of single PIN photodiodes (one sample of each photodiode type) and two samples formed by connecting multiple photodiodes in parallel (two BPW34 photodiodes in parallel and four BPW34 photodiodes in parallel). The samples have been irradiated with a ^{60}Co gamma ray source and the relations between the induced photocurrent and the dose rate, and between the accumulated charge and the absorbed dose, have been determined. For measuring the photodiodes response, a custom made auto-ranging electrometer controlled by a personal computer, and capable of measuring direct currents from 50 pA to 10 A with relative error less than 2.5%, has been used. Obtained results have shown very good linearity between the dose rate and the induced photocurrent for dose rates ranging from 0.93 Gy/h to 67 Gy/h. Also, very good linearity has been observed between the accumulated charge and the absorbed dose for all tested samples, within the investigated range of absorbed doses from 472 Gy to 3.3 Gy. On the basis of the obtained results, a simple model has been derived, enabling the estimation of the photodiode's current response as a function of the dose rate and the photodiode's geometry (active area and depletion layer width).

Key words: current mode radiation dosimeter, PIN photodiode, auto-ranging electrometer

INTRODUCTION

The current mode dosimeters are widely used for monitoring high intensity (high dose rate) ionizing radiation sources in numerous applications in scientific research, industry, and medicine [1-3]. Generally, the main elements that constitute a current mode dosimeter are the sensor which produces a direct current under radiation exposure and the electrometer for measuring the radiation induced current. The linear relationship between the intensity of the radiation induced current and the dose rate is the basis of the current mode dosimetric applications [4, 5]. Therefore, the dose rate can be determined by measuring the intensity of the radiation induced current, and the integration of that current over a predefined period of time, *i. e.* the exposure time, provides the value of the accumulated charge in the sensor, which is proportional to the absorbed dose [6].

Among a large number of commercially available current read-out radiation sensors, the PIN photodiodes stand out as the best candidates for a variety of practical dosimetric applications. The key advantages of the PIN photodiodes over other conventional current read-out radiation sensors are: high sensitivity, relatively small size, a moderate price, very good linearity, immediate and stable current read-out, possibility of operation without voltage bias, and high quantum efficiency [7].

Because the radiation induced photocurrent flows through a PIN photodiode only during exposure, it is necessary to measure the intensity of that current in real time, *i. e.* while the photodiode is irradiated. The typical values of the radiation induced photocurrents

* Corresponding author; e-mail: marko.andjelkovic2@elfak.ni.ac.rs

vary from picoampere levels up to milliampere levels, depending on the radiation intensity and the characteristics of the PIN photodiode. Measurement of such low level direct currents in a wide dynamic range is accomplished with high performance electrometers. The electrometers for dosimetric applications are commercially available, but they are very expensive. Hence, low cost custom-made electrometers are usually the most efficient solution for general purpose dosimetric applications.

The aim of this study was to evaluate the concept of a current mode dosimeter made up of a commercial PIN photodiode and a custom made electrometer. For that purpose, several Si PIN photodiodes were selected and tested under gamma radiation exposure. The current response for single photodiodes, as well as multiple photodiodes connected in parallel, has been investigated for photovoltaic mode of operation (the photodiodes were not biased). The photodiodes were exposed to gamma radiation from ^{60}Co source and the relation between the induced photocurrent and the dose rate as well as between the accumulated charge and the total absorbed dose were determined. A low cost personal computer-based auto-ranging electrometer, developed in the applied physics laboratory (APL) at the Faculty of Electronic Engineering in Niš, Serbia, was used for real-time measurement of the PIN photodiodes' response.

BASIC PRINCIPLES

The fundamental structure of a PIN photodiode is illustrated in fig. 1. It consists of an intrinsic high-ohmic semiconductor layer implemented between two heavily doped semiconductor regions (n^+ and p^+). As a result of the intrinsic layer, PIN photodiodes have wider depletion layer than ordinary diodes and photodiodes, and hence higher sensitivity to incident radiation.

The major effect of ionizing radiation on the PIN photodiodes is the creation of electron-hole pairs within the depletion layer, which drift under the influence of the corresponding electric field [4]. At high dose rates, a large number of electron-hole pairs is induced in the PIN photodiode's depletion layer, and that is manifested as a stable photocurrent flowing

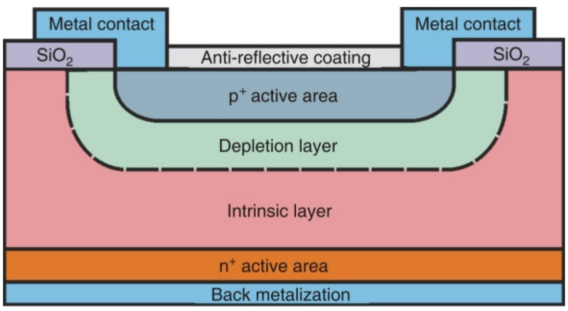

Figure 1. Silicon PIN photodiode cross-section

through the photodiode. The minimum measurable level of the radiation induced photocurrent is limited by the level of dark (leakage) current – the current that flows through the photodiode when it is not exposed to radiation.

Since the PIN photodiodes are sensitive to ambient light as well as infra-red and ultra-violet rays, they must be optically isolated or otherwise the signal induced by the light will overwhelm the radiation induced signal.

The photocurrent response of the PIN photodiodes exposed to ionizing radiation depends on several factors: (1) dose rate, (2) active area of the PIN photodiode, (3) width of the depletion layer, (4) energy of the radiation source, (5) ambient temperature, and (6) orientation of the photodiode with respect to the source.

The dependence of the photocurrent response with the dose rate is used as the main dosimetric parameter in current mode applications [4-6]. Several experimental studies have verified the linear dependence between the radiation induced photocurrent and the dose rate, for a number of commercial PIN photodiodes exposed to X and gamma radiation, in a wide dose rate range [1-3].

Regarding the PIN photodiode's geometry, the parameter that dominantly affects the photocurrent response is the active detection volume, defined as the product of the active area and the depletion layer width. Hence, the PIN photodiodes with a larger active area and/or a wider depletion layer are expected to exhibit higher sensitivity to incident radiation [6, 8].

While the active area of a particular photodiode is constant, the depletion layer width can be varied. The width of the depletion layer is determined by the applied reverse bias voltage [8]. If the photodiode is operated in the photovoltaic mode (without bias), the depletion layer width is minimum. On the other hand, when the photodiode is operated in the photoconductive mode (with reverse bias voltage), the depletion layer width increases proportionally to the applied reverse voltage. The photoconductive mode provides higher sensitivity, but also leads to the increase of the leakage current, limiting the minimum dose rate that can be measured. Otherwise, the photovoltaic mode ensures the lowest leakage current, but at the expense of a lower sensitivity because of the minimum depletion layer width. In practical current mode applications, the photovoltaic mode is often preferred because of minimum leakage current.

The photodiode's response depends on the energy of the radioactive source [8]. A number of investigations have demonstrated that the energy dependence is most pronounced for energies below 200 keV [9, 10]. For that reason, the PIN photodiodes should be energy compensated when used in low energy range.

The ambient temperature has a significant impact on the PIN photodiode's current response. The increase of temperature leads to the increase of the photodiode's leakage current, and as a consequence limits the lowest measurable dose rate [8, 9].

The level of the induced photocurrent depends to a large extent upon the orientation of the PIN photodiode with respect to the source [9]. This directional dependence is due to the construction of the photodiode as well as the nature of the source. Flat photodiodes exhibit larger directional dependence than the rounded ones. Similarly, the directional dependence is more dominant in X-ray fields than in gamma ray fields [8, 9].

A serious problem with PIN photodiodes is their vulnerability to structural damages caused by ionizing radiation. The main factors contributing to the radiation induced damages in PIN photodiodes are the absorbed dose and the energy of the radioactive source. If the PIN photodiode is exposed to high doses and/or high energy radioactive sources, the structural damages of the silicon crystalline lattice are induced, resulting in the increase of the dark (leakage) current [4, 8-10]. In addition, the radiation induced damages lead to the gradual decrease of the level of radiation induced photocurrent, *i. e*. decrease of the PIN photodiode's sensitivity. The level of sensitivity loss as a function of radiation damage depends on the photodiode's characteristics, energy of the source and total absorbed dose. Hence, the dosimeters based on PIN photodiodes must be recalibrated periodically to ensure long term stability and accuracy.

PIN PHOTODIODES SELECTION

Three commercial PIN photodiodes were selected for evaluation: S1223 (Hammamatsu), BPW34 (Osram), and PS100-6-CER2 PIN (First Sensor). The physical view of the photodiodes is shown in fig. 2, while their main characteristics are outlined in tab. 1.

The main aspects considered during the selection of the PIN photodiodes were the active area and the dark current level. For the purpose of comparison, the PIN photodiodes with different active areas and as low dark current levels as possible, have been chosen.

Five test samples were prepared for experimental investigation:

- Sample 1: a single S1223 photodiode,
- Sample 2: a single PS100-6-CER2 PIN photodiode,
- Sample 3: a single BPW34 photodiode,
- Sample 4: two BPW34 photodiodes connected in parallel, and

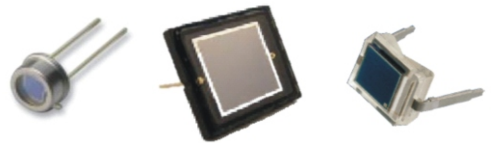

Figure 2. PIN photodiodes used for experimental testing (from left to right: S1223, PS100-6-CER2 PIN, BPW34; the photographs are not scaled)

Table 1. PIN photodiode characteristics

	S1223	PS100-6-CER2 PIN	BPW34
Active area [mm^2]	6.6	100	7.5
Junction capacitance without bias [pF]	71.79	796.17	79.9
Dark current without bias [pA]	3	4.2	2.1
Depletion layer width without bias [μm]	1.07	1.47	1.096
Maximum reverse voltage [V]	30	100	60
Price per unit (€)	12	55	1.1

- Sample 5: four BPW34 photodiodes connected in parallel.

The dark current, junction capacitance and depletion layer width without voltage bias have been determined experimentally.

For each sample, the dark current was measured with Keithley 2636A source-measuring unit. The dark current levels for samples 4 and 5 were approximately 4.3 pA and 8.4 pA, respectively.

The junction capacitance was determined from the C-V curves measured by the Keithley 4200-SCS semiconductor characterization system. With known capacitance C and active area A, the depletion layer width w was calculated using the equation

$$w \quad \frac{\varepsilon A}{C} \tag{1}$$

where ε = 11.68 (dielectric constant of silicon). For samples 4 and 5, w was considered to be the same as for sample 3, while C was calculated as the sum of capacitances connected in parallel.

The photodiodes were soldered on printed circuit boards (PCB), and a BNC connector was installed on each PCB for interfacing with the measurement system. To achieve appropriate optical isolation, the photodiodes were wrapped with light-proof foil.

AUTO-RANGING ELECTROMETER

A prototype of an inexpensive custom made PC-based electrometer was used for real-time measurement of the PIN photodiodes' response [11]. The electrometer was designed specially for current mode dosimetric applications, and it is the first prototype of such instrument constructed in the Applied Physics Laboratory at the Faculty of Electronic Engineering in Niš, Serbia.

The electrometer supports direct current measurements in five sensitivity ranges:

- Range 1: below 1 nA,
- Range 2: from 1 nA to 10 nA,
- Range 3: from 10 nA to 100 nA,

– Range 4: from 100 nA to 1   A, and
– Range 5: from 1   A to 10   A.

A very important feature of the developed electrometer is the auto-ranging capability. This means that the electrometer can automatically detect the range to which the input current belongs, and accordingly adjust the appropriate settings for that range. Switching from one range to the other is also achieved automatically, on the basis of a specific range switching algorithm.

The electrometer is PC-dependent, meaning that a personal computer equipped with a suitable application software is required for controlling its operation, as well as for data processing, visualization and storage. Such concept was adapted to simplify the electrometer design and to enable its implementation in a wide variety of practical dosimetric applications.

System architecture

In order to provide easier testing and upgrade, the electrometer was realized as a modular system with two functional units:
– current-to-voltage converter (IVC), and
– control unit (CU).

The architecture of the developed electrometer, illustrating the main elements and the interconnections between them, is presented in fig. 3.

The IVC transforms the incoming current into a proportional voltage on the principle of transimpedance gain [12]. The constitutive elements of the IVC are: a variable gain transimpedance amplifier, an inverting amplifier, and a gain switching logic.

The variable gain transimpedance amplifier consists of AD549J, an electrometer grade operational amplifier from Analog Devices, and five resistors in the operational amplifier's negative feedback for gain setting.

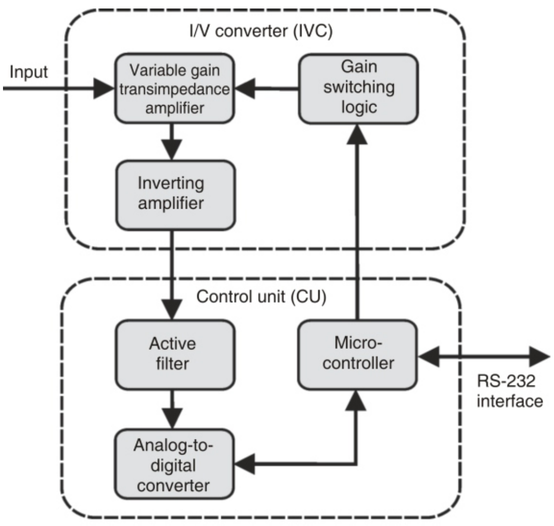

Figure 3. Block diagram of the custom made electrometer

Switching of the resistors, *i. e.* range selection, is performed by ADG452, a very low leakage quad analog switch, manufactured by Analog Devices. The control of the switching is accomplished by the microcontroller from the control unit.

To achieve wider dynamic range, the voltage from the transimpedance stage is amplified with an inverting amplifier having a nominal gain of -10. The gain stage is based on a dual operational amplifier OPA2111, manufactured by Burr Brown.

The CU performs automatic selection of the measurement range, digitization of the voltage generated by the IVC, and transfer of digitized data to the PC. Its main elements are: a microcontroller (MCU), an analog-to-digital converter (ADC), a low pass filter, and a serial RS-232 interface for PC connectivity.

Microcontroller is the central processing element within the CU. In this case, a general purpose 8-bit microcontroller PIC16F887, from Microchip, is used. It is equipped with a firmware, developed in a C-based compiler, which implements the aforementioned tasks.

A 12-bit analog-to-digital converter AD1674, from Analog Devices, is used for digitizing the voltage from the IVC. The key features of this ADC are: parallel output, unipolar and bipolar input modes supporting voltages up to 20V, conversion speed of 10 μs, sampling rate of 100 ksps, and on-chip voltage reference.

Before being processed in the analog-to-digital converter, the signal from the IVC is filtered to minimize the noise that might have been superimposed on the signal. Filtering is achieved by a third order active low pass Butterworth filter, based on a dual operational amplifier OPA2111, with the cut-off frequency of 1 Hz.

The communication between the MCU and the PC is established over serial RS-232 interface realized with a standard logic level translator MAX232. The fullduplex configuration with two data lines and transfer rate of 9600 bits per seconds, is utilized.

PC application software

A PC equipped with application software, developed in the Visual C# Express software development environment, is used for real-time monitoring of the electrometer read-out and data acquisition. The main functions of the application software are: (1) allows the user to start and stop the electrometer read-out by issuing adequate commands, (2) converts the measured voltage into current, (3) determines the elapsed time between two successive measurements on the basis of the data obtained from PC's real-time clock, (4) displays the measured current values and the measurement counts on the PC monitor, and (5) stores the measured current values and the elapsed time values in appropriate files on the PC hard drive.

Calibration procedure

The electrometer was calibrated with a high precision source measuring unit model Keithley 2636A. Predefined direct current values were injected into the electrometer input by the source-measuring unit, and the corresponding response was recorded with a PC, using the custom made application software for monitoring the electrometer operation. The input current levels were compared with the values measured by the electrometer and the relative error was calculated [11].

It was determined that the electrometer is capable of measuring currents from 50 pA to 100 pA with relative error less than 2.5%, and from 100 pA to 10   A with relative error less that 1%. Even the currents below 50 pA (typically down to 10 pA) can be measured but with relative error up to 10%. Although these results are comparable with some custom made designs reported in literature [12-14], they are still inferior to commercial electrometers which are capable of measuring direct currents in a wider dynamic range (up to nine decades) with much lower relative error (below 0.1%).

The realized electrometer has a constant response time of 1.83 seconds in all measurement ranges. Basically, the response time is the total time interval required for measurement, data processing, and transfer of digitized data to the PC. The response time practically determines the resolution of the dose measurement (dose = dose rate × time) and for that reason it would be beneficial to have as low response time as possible. Nevertheless, this solution is competitive even with commercially available dosimetric electrometers that have a response time of around 1 s [15, 16].

Physical design

Figure 4 shows the photograph of the assembled auto-ranging electrometer. The IVC is enclosed in a metal case (15 cm × 10 cm × 5 cm), while the CU is housed in a plastic box (16 cm × 16 cm × 6.5 cm).

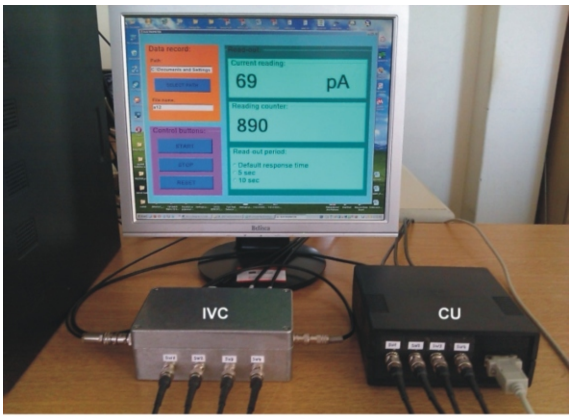

Figure 4. Auto-ranging electrometer in operation

Both units are powered from a custom made regulated power supply unit (not shown in fig. 4) which provides three voltage levels: +15 V, –15 V, and +5 V. The total current consumption of the system is relatively low, approximately 70 mA.

The connections between the IVC and CU, as well as between these units and external modules (power supply and current source) are achieved through coaxial or triaxial cables, while the connection with the PC is carried out through RS-232 cable.

EXPERIMENTAL PROCEDURE

The experimental evaluation of the proposed dosimeter was performed in the Metrology Laboratory of the Vinča Institute of Nuclear Sciences, Belgrade, Serbia. The samples were irradiated at room temperature (~25 °C), using a ^{60}Co gamma ray source.

During irradiation, the samples were isolated in a special irradiation chamber containing the ^{60}Co gamma radiation source. They were operated in the photovoltaic mode (without voltage bias), and the connection with the measurement system, located in a separate room, was achieved through a 5 m RG-58 coaxial cable. The parameters measured during the experiment were the induced photocurrent and the irradiation time. Figure 5 illustrates the complete experimental set-up.

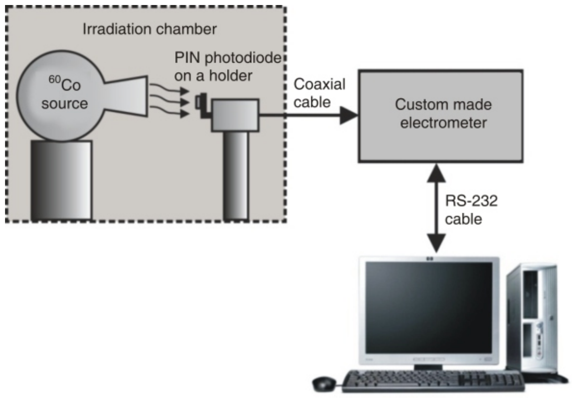

Figure 5. Experimental set-up

The samples were positioned in front of the ^{60}Co source, at different distances from the source, where each distance was equivalent to a specific dose rate value. Each test sample was irradiated at 12 different distances from the source. For each distance the dose rate was calculated from one reference distance for which the dose rate value was measured with reference dosimeter. The list of all source-to-sample distances at which the measurements were conducted and the corresponding dose rate values are given in tab. 2. Each irradiation session lasted 3 minutes and a total of 98 readings were acquired per irradiation session.

Table 2. Distances at which the samples were irradiated and corresponding dose rate values

Distance from the source [cm]	Dose rate [Gyh^{-1}]
40	67
50	42.88
60	29.78
70	21.88
80	16.75
110	8.86
140	5.45
170	3.71
200	2.68
240	1.86
290	1.27
340	0.93

RESULTS AND DISCUSSION

The objective of the experimental research was to investigate the effects of gamma radiation on the electrical parameters of the selected PIN photodiodes. Hence, the two relations have been analyzed:
- the relation between the intensity of the radiation induced photocurrent and the dose rate, and
- the relation between the accumulated charge and the absorbed dose.

Relation between the intensity of the radiation induced photocurrent and the dose rate

The relation between the photocurrent response and the dose rate, as well as the stability of the radiation induced photocurrent, are the most important parameters which determine the applicability of a PIN photodiode as the radiation detector. The waveforms illustrating the variation of the induced photocurrent as a function of irradiation time, for all twelve irradiation sessions and all five samples, are presented in figs. 6-10.

It can be seen that the level of the radiation induced photocurrent was very stable during all irradiation sessions, for all five samples. Though, it is worth noting that the photocurrent level was not constant, but slight fluctuations have been observed with a maximum relative deviation less than 6% in all cases.

The lowest measured photocurrent level for each sample was more than two orders of magnitude higher than the nominal dark current before irradiation. The level of the dark current was measured before and after each irradiation session, and no significant changes between the pre-irradiation and the post-irradiation dark current levels were observed. This indicates that no considerable damage to the photodiodes' structure was induced during irradiation.

With the obtained results it is possible to determine the functional relations between the radiation induced photocurrent and the dose rate. The results acquired from each irradiation session have been averaged to obtain a mean photocurrent value for each dose rate value. Figure 11 illustrates the relation be-

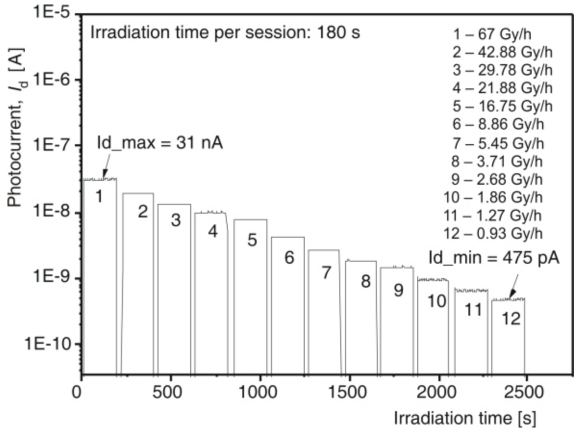

Figure 6. Induced photocurrent *vs*. irradiation time for various dose rates for sample 1

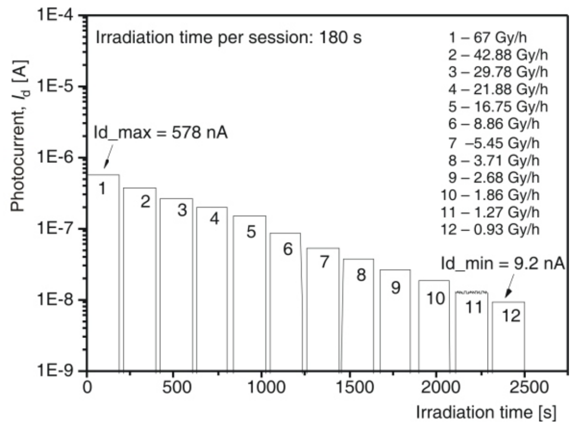

Figure 7. Induced photocurrent *vs*. irradiation time for various dose rates for sample 2

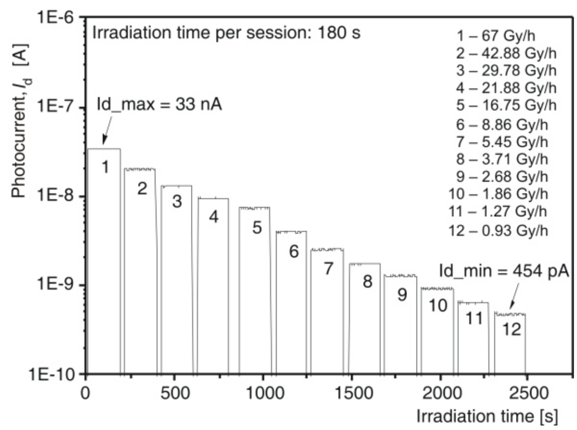

Figure 8. Induced photocurrent *vs*. irradiation time for various dose rates for sample 3

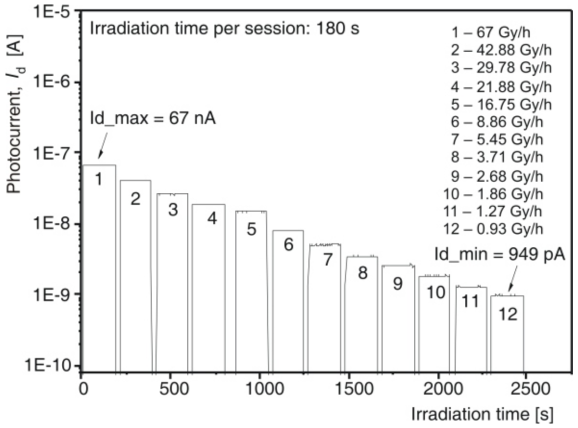

Figure 9. Induced photocurrent *vs*. irradiation time for various dose rates for sample 4

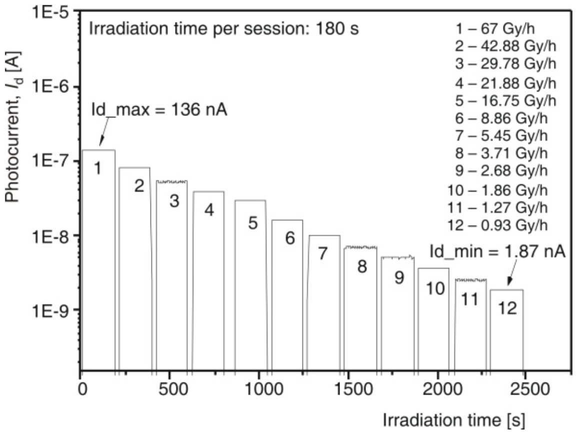

Figure 10. Induced photocurrent versus irradiation time for various dose rates for sample 5

tween the dose rate and the mean photocurrent values for all samples.

A linear fitting was applied to determine the analytical expressions for the relationship between the induced photocurrent and the dose rate. The experimental data has been fitted with the equation $I_D = SD_R + I_{DARK}$, where I_D, D_R, and I_{DARK} are the radiation induced photo-current, dose rate, and dark current, respectively, while S is the "photocurrent *vs*. dose rate" sensitivity. The following are the obtained mathematical relations and the correlation coefficients R^2:

Sample 1:

$$I_D \quad 4.61\ 10^{10} D_R \quad 3\ 10^{12}, (R^2 \quad 0.99886) \quad (2)$$

Sample 2:

$$I_D \quad 8.78\ 10^{9} D_R \quad 4.2\ 10^{12}, (R^2 \quad 0.99331) \quad (3)$$

Sample 3:

$$I_D \quad 4.81\ 10^{10} D_R \quad 2.1\ 10^{12}, (R^2 \quad 0.99543) \quad (4)$$

Sample 4:

$$I_D \quad 9.61\ 10^{10} D_R \quad 4.3\ 10^{12}, (R^2 \quad 0.99543) \quad (5)$$

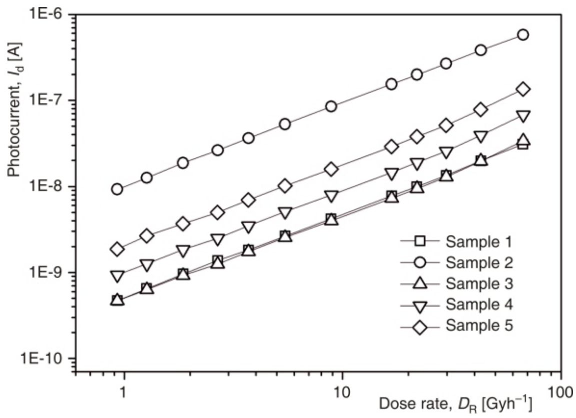

Figure 11. Induced photocurrent as a function of dose rate

Sample 5:

$$I_D \quad 1.92\ 10^{9} D_R \quad 8.4\ 10^{12}, (R^2 \quad 0.99543) \quad (6)$$

Very good linearity between the radiation induced photocurrent and the dose rate was observed for all five samples, within the range of dose rates from 0.93 Gy/h to 67 Gy/h. It seems that even lower dose rates could be measured with all examined samples, since the values of the photocurrents measured for lowest dose rate were considerably higher than the nominal dark currents. However, it is not possible to estimate the behaviour of the photocurrent response for lower dose rates on the basis of the presented results. Thus, further experimental research must be conducted to assess this issue.

The results for single PIN photodiode samples have shown that the "photocurrent *vs*. dose rate" sensitivity is proportional to the PIN photodiode's active area. The highest sensitivity was recorded for sample 2 (PS100-6-CER2 PIN photodiode), 8.78 nA·Gy^{-1}·h, while the sensitivities for sample 1 (S1223 photodiode) and sample 3 (BPW34 photodiode) were 461 pAGy^{-1}h and 481 pAGy^{-1}h, respectively. This can be explained by the fact that sample 2 has the largest active area and widest depletion layer. Hence, it has the largest active volume, which enables the creation of more electronhole pairs than in other samples, resulting in higher radiation induced photocurrent level.

Comparison of the results for samples based on the BPW34 PIN photodiode has confirmed that the sensitivity is linearly proportional to the number of PIN photodiodes connected in parallel. By connecting multiple PIN photodiodes in parallel, the effective detection area increases, and therefore the detection volume also increases, resulting in the increase of the sensitivity. The sensitivity of sample 4 (two BPW34 photodiodes in parallel) was 961 pAGy^{-1}h, which is twice higher than the sensitivity of sample 3 (single BPW34 photodiode). Similarly, the sensitivity of sample 5 (four BPW34 photodiodes in parallel) was

1.92 nAGy^{-1}h, which is four times higher than the sensitivity of sample 3 (single BPW34 photodiode), and twice higher than the sensitivity of sample 4 (two BPW34 photodiodes in parallel). Thus, the sensitivity of a single large area photodiode can be achieved by connecting a number of smaller photodiodes in parallel. However, the main drawback of this approach is that the dark current increases linearly with the number of photodiodes connected in parallel.

Using the obtained results, and known parameters of the PIN photodiodes given in tab. 1, it is possible to derive a mathematical expression for the dependence between the induced photocurrent and the parameters that predominantly influence the photodiode's response (dose rate, active area, and depletion layer width).

The general equation for radiation induced current response of the PIN photodiode is [8]

$$I_{\mathrm{D}} \quad kAwD_{\mathrm{R}} \tag{7}$$

where A, w, and D_{R} represent the active area, depletion layer width, and dose rate, respectively, and k is the coefficient determined by the technological parameters of the PIN photodiode production process. These parameters are proprietary and are not available. However, it is possible to determine the approximate value of k experimentally, for commercial samples.

For a general case, where the dark current I_{DARK} is considered, and where it is possible to have a number n of PIN photodiodes connected in parallel, the current response model may be expressed as:

$$I_{\mathrm{D}} \quad n(kAwD_{\mathrm{R}} \quad I_{\mathrm{DARK}}) \tag{8}$$

By comparing eq. 8 with eqs. 2-6, it can be deduced that:

$$k \quad \frac{S}{nAw} \tag{9}$$

Since S has been obtained experimentally for each sample, the values of k can be easily determined from eq. 9. Hence, k = 6.52 10^{-5} (sample 1), k = = 5.97 10^{-5} (sample 2), k = 5.85 10^{-5} (sample 3), k = = 5.85 10^{-5} (sample 4), and k = 5.84 10^{-5} (sample 5). A very good agreement between the calculated values of k can be observed, with a mean value k_{mean} = 6 10^{-5}, and relative deviation less than 8.7%.

Substituting the mean value of k into eq. 8, the model of the radiation induced photocurrent response, for dose rates from 0.93 Gy/h to 67 Gy/h, becomes,

$$I_D \quad n(6\ 10^{\ 5} AwD_{\mathrm{R}} \quad I_{\mathrm{DARK}}) \tag{10}$$

With the obtained equation it is possible to estimate the radiation induced current response of a PIN photodiode prior to irradiation, and hence evaluate the influence of the photodiode's geometry and dose rate on the level of the induced photocurrent.

Relation between the accumulated charge and the absorbed dose

In practical dosimetric applications it is necessary to known the absorbed dose. If the dose rate is constant, the total dose absorbed during the exposure time τ can be easily calculated as the product of dose rate and τ. In other words, the absorbed dose can be estimated from the measured photocurrent I_{D} and the exposure time τ.

Basically, the product of the photocurrent and the exposure time represents the charge accumulated in the photodiode during a time interval τ. This means that the total absorbed dose may be expressed in terms of accumulated charge.

The relation between the accumulated charge Q and the absorbed dose D, obtained for the dose rate of 67 Gy/h, is illustrated in fig. 12. This dependence is, as it was expected on the basis of the results from fig. 11, linear. For each sample the "charge *vs*. dose" sensitivity S_{D} has been determined by linear fitting with the equation $Q = S_{\mathrm{D}}D$. The sensitivities were: 1.65 C/Gy (sample 1), 31.2 C/Gy (sample 2), 1.81 C/Gy (sample 3), 3.63 C/Gy (sample 4), and 7.33 C/Gy (sample 5).

For the dose rate of 67 Gy/h, the minimum measured dose was 34 mGy and the maximum dose was 3.3 Gy. The value of the minimum dose is determined by the electrometer's response time. Since the electrometer has a response time of 1.83 s (0.00050833 h), the total dose after the time interval 0.00050833 h, for dose rate of 67 Gy/h, is 67 0.00050833 = 34 mGy. For lower dose rates, the minimum measurable dose is smaller. As an example, the lowest measured dose during the experiment was 472 Gy, for dose rate of 0.93 Gy/h.

To determine the dependence between the "charge *vs*. dose" sensitivity and the dose rate, the functional relation $Q = f(D)$ was derived for all dose rates, and for each sample the "charge *vs*. dose" sensitivity was determined. The variation of the "charge *vs*. dose" sensitivities with the dose rate is depicted in fig. 13.

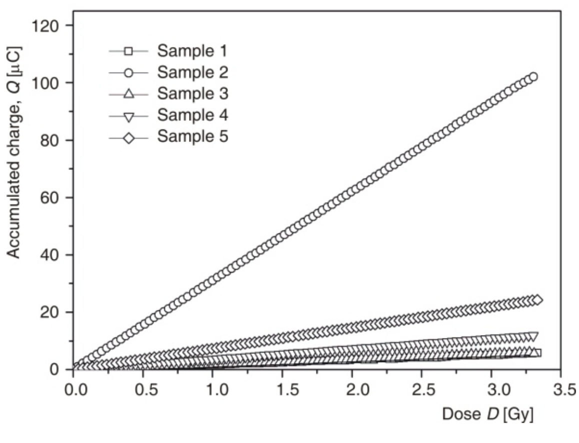

Figure 12. Accumulated charge as a function of the total absorbed dose (for dose rate of 67 Gy/h)

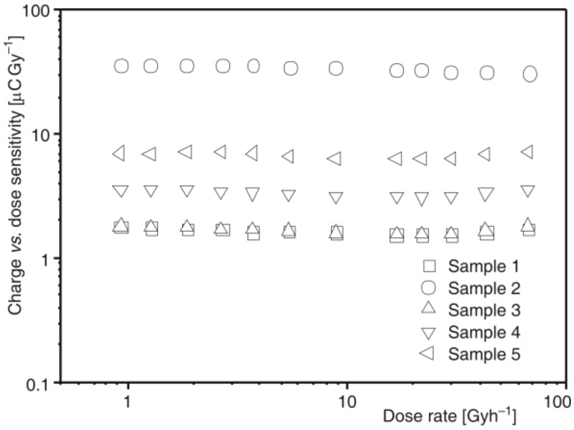

Figure 13. Charge *vs*. dose sensitivity as a function of dose rate

The "charge *vs*. dose" sensitivities were uniform for all samples, within dose rate range from 0.93 Gy/h to 67 Gy/h, with a maximum relative deviation of 8%. This means that the "charge *vs*. dose" sensitivity is independent of the dose rate. Consequently, the absorbed dose can be determined on the basis of accumulated charge, without calculating the dose rate.

CONCLUSIONS

In this paper an experimental evaluation of the current-mode gamma radiation dosimeter, based on a commercial PIN photodiode and a custom made auto-ranging electrometer, was discussed. Three different types of commercial PIN photodiodes were chosen for evaluation (S1223, BPW34 and PS100-6-CER2 PIN), and a total of five samples have been characterized – three single PIN photodiode samples (one sample of each type) and two samples with multiple photodiodes (two BPW34 photodiodes connected in parallel and four BPW34 photodiodes connected in parallel).

The samples have been irradiated for 3 minutes in a continuous gamma radiation field from a ^{60}Co gamma ray source, and the corresponding photocurrent response was recorded with a custom made auto-ranging electrometer controlled by a PC. The electrometer supports direct current measurements from 50 pA up to 10 A in five sensitivity ranges, with relative error below 2.5%, and a nominal response time of 1.83 s.

Acquired results have shown very good linearity between the induced photocurrent and the dose rate for the investigated range of dose rates from 0.93 Gy/h to 67 Gy/h. The radiation induced photocurrent response was very stable for all examined samples. The results have also confirmed very good linearity between the accumulated charge and the absorbed dose within the investigated dose range from 472 Gy to 3.3 Gy.

In the case of single photodiodes, it was demonstrated that the sensitivity is proportional to the active area of the photodiode. The effective detection area, and hence the sensitivity, can also be increased by connecting multiple photodiodes in parallel. For multiple PIN photodiodes connected in parallel, the sensitivity is directly proportional to the number of PIN photodiodes connected in parallel. Using the experimental results, a generalized model of the PIN photodiode's current response has been derived, that can be used for analytical evaluation of the PIN photodiode's response under gamma radiation exposure.

Therefore, it can be concluded on the basis of the preliminary evaluation that the examined PIN photodiodes can be used as the current mode gamma radiation sensors in various dosimetric applications. The examined PIN photodiodes, together with the developed autoranging electrometer, represent a very good basis for a gamma radiation current mode dosimeter. Depending on practical requirements, it is possible to use either single or multiple photodiodes configuration.

However, further work must be undertaken in order to determine the optimum design of the proposed current mode dosimeter. Future work will be focused both on improving the performance of the auto-ranging electrometer, as well as on more detailed characterization of the PIN photodiodes.

As far as the electrometer design is considered, the improvements will be oriented towards achieving higher measurement accuracy, wider dynamic range and faster response. Beside that, the design will be modified to provide a compact solution that will have the capability of stand-alone operation, and thus be more competitive with commercial electrometers.

The characterization of the PIN photodiodes will be extended in order to provide a better insight into the behaviour of PIN photodiodes under gamma radiation exposure. In that sense, a larger number of PIN photodiodes with different characteristics will be used to evaluate the obtained model of the radiation induced current response. In addition, the three aspects that have not been analyzed in this study will be thoroughly examined: the photocurrent response for dose rates lower than 0.93 Gy/h, the effects of higher total doses on the level of the radiation induced photocurrent, and the reproducibility of the induced photocurrent. The results obtained from these tests will be helpful for estimating the level of the radiation induced damages in the PIN photodiodes.

ACKOWLEDGEMENT

This work was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia under the project 43011. The authors would also like to thank the staff of the Metrology Laboratory at the Vinča Institute of Nuclear Sciences, Vinča, Belgrade, Serbia, for technical support in the realization of experimental testing.

AUTHOR CONTRIBUTIONS

Theoretical analysis and experimental procedure were carried out by M. S. Andjelković and G. S. Ristić. Both authors have analyzed and discussed the results. The manuscript was written and the figures were prepared by M. S. Andjelković.

REFERENCES

[1] Ferreira, D. C., *et al*., Use of a PIN Photodiode for Dosimetric Purposes in Radiation Processing, 2009 International Nuclear Atlantic Conference – INAC 2009, Rio de Janeiro, Brazil, September 27 to October 2, 2009
[2] Paschoal, C. M. M., Souza, D. do N., Santos, L. A. P., Characterization of Three Photodetector Types for Computed Tomography Dosimetry, *World Academy of Science, Engineering and Technology, 56* (2011), pp. 92-95
[3] Aoyama, T., *et al.*, An in-Phantom Dosimeter System Using PIN Silicon Photodiode Radiation Sensors for Measuring Organ Doses in X-Ray CT and other Diagnostic Radiology, *Medical Physics, 29* (2002), 1504 (7 pages)
[4] Knoll, G. F., Radiation Detection and Measurement. John Wiley & Sons, New York, USA, 2000
[5] Barthe, J., Electronic Dosimeters Based on Solid State Detectors, *Nuclear Instruments and Methods in Physics Research B, 184* (2001), 1-2, pp. 158-189
[6] Rosenfeld, B. A., Electronic Dosimetry in Radiation Therapy, *Radiation Measurements, 41* (2007), S1, pp. 134-153
[7] Bueno, C. C., *et al*., Response of PIN Photodiodes as Room Temperature Detectors, *Applied Radiation and Isotopes, 61* (2004), 6, pp. 1341-1347
[8] Lanza, J. J., An Automated Dosimetry System for Computed Tomography X-Ray Scanners Using PIN Photodiodes, Ph. D. thesis, University of Florida, Gainesville, Fla., USA, 1979
[9] Amarjit, S. S., In-vivo Radiation Diode Dosimeter for Thera-peutic Photon Beams, Ph. D. thesis, University of South Florida, Tampa, Fly., USA, 2007
[10] Wittenburg, K., Radiation Damage in PIN Photodiodes, *Nuclear Instruments and Methods in Physics Research A, 270* (1988), 1, pp. 56-62
[11] Andjelković, M., Ristić, G. S., An Auto-Ranging Electrometer for Current Mode Dosimetry, *Proceedings*, First International Conference on Radiation and Dosimetry in Various Fields of Research – RAD 2012, Niš, Serbia, April 25 to 27, 2012, pp. 113-116
[12] Sen-Yen, S., Ruey-Shyan, C., A Novel Wide Range Electrometer with Quasilinear Output, *Review of Scientific Instruments, 68* (1997), 10, pp. 3917-3919
[13] He, M., Marzoca, P., Dhaniyala, S., A New High Preformance Battery Operated Electrometer, *Review of Scientific Instruments, 78* (2007), 10, pp. 105103-105103-5
[14] Rajput, S. S., Garg, S. C., A High Resolution Autogain Ranging Linear Electrometer Amplifier, *Review of Scientific Instruments, 67* (1996), 2, pp. 609-611
[15] ***, Dose-1 Electrometer User Manual, www.iba-dosimetry.com
[16] ***, Model 206 Electrometer User Manual, www.cnmcco.com

Received on September 26, 2012
Accepted on February 25, 2013

Марко С. АНЂЕЛКОВИЋ, Горан С. РИСТИЋ

ИСПИТИВАЊЕ МОГУЋНОСТИ ПРИМЕНЕ ДОЗИМЕТРА ГАМА ЗРАЧЕЊА У СТРУЈНОМ РЕЖИМУ РАДА ЗАСНОВАНОГ НА КОМЕРЦИЈАЛНОЈ ПИН ФОТОДИОДИ И НАМЕНСКИ РАЗВИЈЕНОМ ЕЛЕКТРОМЕТРУ СА АУТОМАТСКИМ ПОДЕШАВАЊЕМ ОПСЕГА

Спроведено је експериментално испитивање могућности примене дозиметра гама зрачења предвиђеног за рад у струјном режиму, који се састоји од комерцијалне ПИН фотодиоде као сензора гама зрачења и наменски развијеног електрометра са аутоматским подешавањем опсега којим се мери одзив ПИН фотодиоде под дејством зрачења. Анализиран је струјни одзив под дејством зрачења за појединачне ПИН фотодиоде са различитим активним површинама, као и за више ПИН фотодиода везаних у паралели. Изабрана су три типа ПИН фотодиода (S1223, BPW34 и PS100-6-CER2 ПИН) док је у самом експерименту тестирано 5 узорака – три појединачне ПИН фотодиоде (по један узорак сваког типа) и два низа ПИН фотодиода (паралелна веза две и четири BWP34 ПИН фотодиоде). Тестни узорци су зрачени ^{60}Co гама извором, и за сваки узорак су измерене зависности између индуковане фотострује и јачине дозе, као и између акумулираног наелектрисања и укупне апсорбоване дозе. За потребе мерења фотострује и акумулираног наелектрисања коришћен је наменски развијен електрометар контролисан персоналним рачунаром. Реализовани електрометар подржава мерење једносмерних струја у опсегу од 50 pA до 10 mA са релативном грешком мањом од 2.5%. Добијени резултати указују на веома добру линеарност између јачине дозе и нивоа фотострује за свих пет тестна узорка, у опсегу јачина дозе, за све узорке. Максималне и минималне измерене дозе биле су 3.3 Gy и 472 mGy, респективно. На основу добијених резултата формиран је модел који описује одзив фотодиоде, на основу којег је могуће проценити струјни одзив ПИН фотодиоде у зависности од јачине дозе и геометрије ПИН фотодиоде (активне површине и ширине осиромашене области).

Кључне речи: дозиметар у струјном режиму рада, ПИН фотодиода, електрометар са аутоматским подешавањем опсега